Single Multicore-Fiber Bidirectional Spatial Channel Network Based on Spatial Cross-Connect and Multicore EDFA Efficiently Accommodating Asymmetric Traffic

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Abstract: A single multicore-fiber bidirectional spatial channel network that efficiently accommodates asymmetric traffic is proposed and demonstrated using a core-selective-switch-based spatial cross-connect with an $M \times N$ wavelength-selective switch and a bidirectional multicore EDFA with reversible optical isolators.

1. Introduction

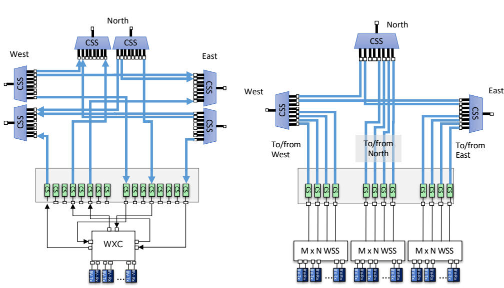
Except for access networks, current optical networks symmetrically allocate bandwidth to the upstream and downstream. This is because the traffic asymmetry observed in access networks is expected to be flattened by the statistical multiplexing effect as traffic aggregates in metro and core networks. Unfortunately, non-negligible traffic asymmetry is observed in current large IP networks [1], and in the forthcoming Beyond 5G era, the progress in cloud computing may further increase the traffic asymmetry. In such a situation, the wasted link capacity in the under-loaded direction can no longer be overlooked, especially in submarine optical cable systems where the number of fibers accommodated in a cable is limited. An initial study that explored the possible benefits of asymmetric optical connections was reported in the early 2010s and found that using unidirectional circuits to establish asymmetric connections can provide significant cost savings [1]. As far as we know, since then there have been few studies that investigated asymmetric optical networks. On the other hand, steady progress has been made in the fields of bandwidth variable (BV) transponders [2], highly flexible reconfigurable optical add drop multiplexers [3], and spatial division multiplexing technologies such as multicore fibers (MCFs) [4], multicore erbium-doped fiber amplifiers (MC-EDFAs) [5], and spatial channel networks (SCNs) [6] based on spatial cross-connects (SXCs) [7] that employ core selective switches (CSSs) [8]. These areas of progress motivated us to investigate SCNs that can efficiently accommodate asymmetric IP traffic by employing such recent advances.

In this paper, we propose a single-MCF SCN architecture that has bidirectional links comprising a single MCF and that efficiently accommodates up and down asymmetric traffic. We present a feasibility demonstration of the asymmetric bandwidth allocation in a single-MCF SCN using SXC and bidirectional MC-EDFA prototypes.

2. Bidirectional Single-MCF HOXC Efficiently Accommodating Asymmetric Traffic

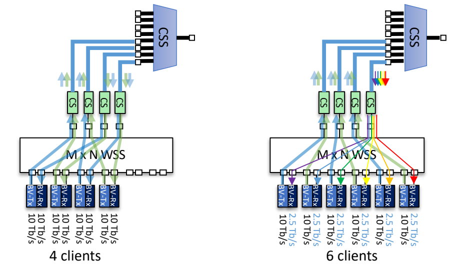
2.1 Conventional Unidirectional Dual-MCF HOXC

Figure 1(a) shows a hierarchical optical cross-connect (HOXC) architecture that comprises a wavelength cross-connect (WXC) and an SXC with an MCF-pair per degree (hereafter referred to as unidirectional dual-MCF SXC.



(a) Dual-MCF unidirectional SXC (b) Single-MCF bidirectional SXC

Fig. 1. SXC architectures.



(a) Symmetric allocation (b) Asymmetric allocation

Fig. 2. Symmetric and asymmetric bandwidth allocations.

The SXC has add/drop connection flexibilities of any-core-access (AC), directional (D), and contention-less (CL), which are achieved by placing ingress and egress 1×8 CSSs in each direction and connecting a core selector (CS) to the add/drop port of the CSSs [8,9]. If the WXC has connection flexibilities of colorless, directionless, and CL, an optical signal sent from a transmitter connected to any client port of the WXC can be multiplexed into any core in an output MCF destined to any direction. Similarly, an optical signal coming through any core of an input MCF from any direction can be received by a receiver connected to any client port of the WXC.

2.2 Bidirectional Single-MCF SXC and M×N WSS

Figure 1(b) shows the proposed bidirectional single-MCF HOXC architecture that comprises $M\times N$ wavelength selective switches (WSSs) and an SXC with a single-MCF per degree. In general, a WSS has one input single mode fiber (SMF) port and N output SMF ports (1×N WSS). An $M\times N$ WSS is a type of a WSS that has N input SMF ports. An $M\times N$ WSS can be formed by connecting M 1×N WSSs and N 1×M optical switches. The 1×N WSSs could be replaced with 1×N splitters (SPLs) to form an $M\times N$ multicast switch (MCS) if used with coherent transponders. A CSS, a CS, and an $M\times N$ WSS are reciprocal devices and can be used by changing the propagation direction for each core. Each CSS in the SXC can connect any core in the line side MCF to the core with the same core number in the line side MCF in the other direction, or to any CS on the client side, regardless of the propagation direction of the optical signal in the core. Hereafter, we refer to this SXC as a bidirectional single-MCF SXC. The SXC has add/drop connection flexibilities of AC/D/CL the same as the unidirectional dual-MCF SXC. An optical signal sent from a transmitter connected to any client port of the $M\times N$ WSS can be multiplexed into any core in the MCF of the CSS to which the $M\times N$ WSS is connected. Similarly, an optical signal coming through any core of the MCF of the CSS can be received by a receiver connected to any client port of the $M\times N$ WSS.

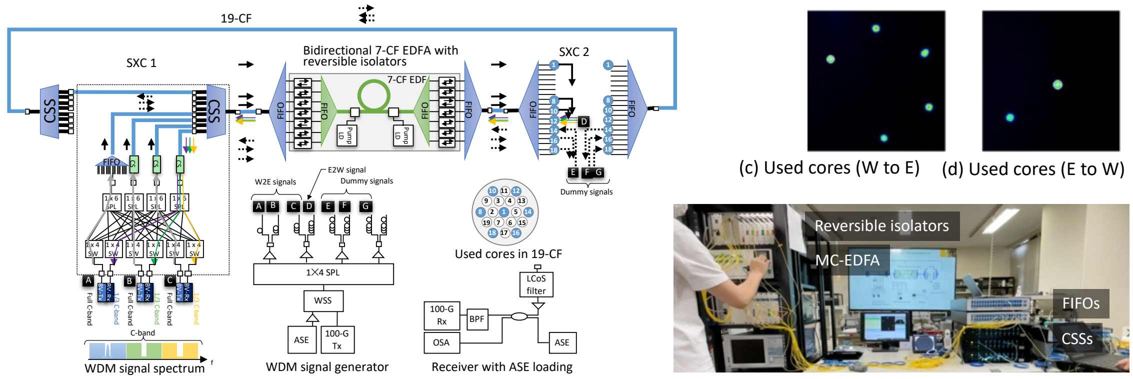
Figure 2 shows how a bidirectional single-MCF HOXC can efficiently accommodate asymmetric traffic. In this figure, only one degree of the SXC in Fig. 1(b) is depicted for simplicity. We assume the use of transponders whose transmitter and receiver bandwidths can be changed independently. Hereafter, we refer to these as bandwidth variable transmitters (BV-Txs) and receivers (BV-Rxs), which support multiple baud-rates or multiple subcarriers. Let us assume that (i) the capacity of each core of the MCF is 20 Tb/s, (ii) the transmission rate variable range of the BV-Tx/Rx is 2.5 Tb/s to 10 Tb/s with a 2.5-Tb/s step, and (iii) the number of usable cores for adding and dropping at this node is 4. If clients require a 10-Tb/s bandwidth for both the upstream and downstream (symmetrical traffic), two 10-Tb/s signals can be multiplexed into a core in the wavelength division multiplexing (WDM) layer using the $M\times N$ WSS. As a result, 4 clients can be accommodated using the available 4 cores as shown in Fig. 2(a). On the other hand, if clients require a 10-Tb/s bandwidth for the upstream and a 2.5-Tb/s bandwidth for the downstream (asymmetric traffic), the accommodable number of clients increases from 4 to 6, because one core among the 4 cores can be shared by six 2.5-Tb/s downstream optical signals that have a reduced spectrum width as shown in Fig. 2(b).

2.3 Bidirectional MC-EDFA with Per Core Reconfigurable Amplification Direction

Another important building block to achieve single-MCF bidirectional SCNs that efficiently accommodate asymmetric traffic flows is a bidirectional MC-EDFA that has the capability to reconfigure independently the amplification direction of a WDM signal for each core. Such a bidirectional MC-EDFA can be constructed by combining a bidirectional cladding-pumped MC-EDFA [5] and reversible optical isolators (ROIs) [10] via a MCF fan-in fan-out (FIFO) device. Here, an ROI is an optical isolator whose transmittable direction can be changed using a 1×2 optical switch and an optical circulator.

3. Feasibility Demonstration of Asymmetric Traffic Accommodation in Single-MCF Bidirectional SCN

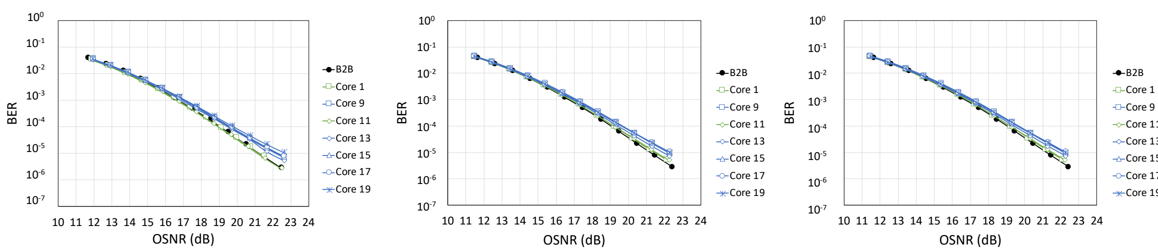
In order to demonstrate the feasibility of single-MCF bidirectional SCNs, we constructed a single MCF ring network testbed as shown in Fig. 3(a) that comprises two 19-core fiber (19-CF) SXCs (SXCs 1 and 2) and a bidirectional 7-core fiber (7-CF) EDFA with ROIs. SXC 1 comprises two 19-CF 1×8 CSS prototypes packaged in a 44-mm diameter, 138-mm long cylindrical housing [9]. Due to the limitation of the available number of CSs, three CSs are attached to three of four add/drop ports of one CSS in SXC 1 and a 19-CF FIFO device [11] is attached to the remaining add/drop port. On the client side of SXC 1, a 4×6 MCS is constructed with four 1×6 SPLs and six 1×4 switches. Due to the limitations of the available number of CSSs, SXC 2 is constructed with two 19-CF FIFO devices. A bidirectional 7-CF EDFA with ROIs is arranged between SXC 1 and SXC 2. Here, 19-CF FIFO and 7-CF FIFO devices are used for the core number conversion and 7 of the 19 cores in the SXCs (see inset in Fig. 3(a)) are used in this demonstration. A pseudo-WDM signal used for the bit error rate (BER) vs. optical signal-to-noise ratio (OSNR) measurements is created by synthesizing the optical signal generated from a 100-Gb/s dual-polarization quadrature phase shift keying transmitter and the dummy optical signal created by spectrally shaping the amplified spontaneous emission (ASE) light. Seven copies of the pseudo-WDM signal are generated using a 1×8 SPL and delay fiber lines to fill all the 7



(c) Used cores (W to E) (d) Used cores (E to W)

(a) Experimental configuration (b) SXC and MC-EDFA prototypes

Fig. 3. Experimental configuration for asymmetric traffic scenario.



(a) 1541 nm (b) 1551 nm (c) 1561 nm

Fig. 4. BER vs. OSNR characteristics for seven signals transmitted through different cores in different directions.

cores in the 7-CF EDFA prototype. Fig. 3(b) shows a photo of the 19-CF SXC and 7-CF EDFA prototypes. The bidirectional cladding pump power is controlled to provide an approximate 12-dB gain for each fully loaded C band WDM signal transmitted through each core in the bidirectional 7-CF EDFA prototype.

We examined two scenarios: (A) each of two clients requires the entire C band in both the west-to-east (WtoE) and east-to-west (EtoW) directions (symmetrical traffic), and (B) each of three clients requires the entire C band in the WtoE direction and 1/3 of the bandwidth of the C band in the EtoW direction (asymmetric traffic). Figure 3(a) shows the experimental configuration for scenario B, where the three clients are accommodated using four cores by independently allocating the required bandwidth in both directions. Figures 4(a) to 4(c) show the BER vs. OSNR performance for seven signals at the wavelengths of 1541 nm, 1551 nm, and 1561 nm, respectively, each transmitted through a different core. The figures show that almost no OSNR penalty is observed at the BER of 10^{-3} for all optical signals transmitted through the single-MCF ring network in different cores and different directions (Figs. 3(c) and 3(d), respectively). We examined symmetric scenario A and obtained similar results.

4. Conclusion

We demonstrated that a single-MCF SXC with an M×N WSS and a bidirectional MC-EDFA with ROIs can efficiently accommodate asymmetric traffic by independently allocating the required bandwidth in each direction.

Acknowledgements

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